APPLICATION OF LASER SCHLIEREN AND MONOCHROMATIC PHOTOGRAPHY TO SOLID PROPELLANT COMBUSTION RESEARCH

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THESIS

APPLICATION OF LASER SCHLIEREN AND MONOCHROMATIC PHOTOGRAPHY TO SOLID PROPELLANT COMBUSTION RESEARCH

by

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Application of Laser Schlieren and Monochromatic Photography to Solid Propellant Combustion Research

by

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ABSTRACT

Ammonium perchlorate (AP)-binder sandwiches and a composite propellant were burned in a combustion bomb at various pressures. A schlieren system equipped with an argon laser was used to study the flame structure. High speed monochromatic motion pictures of solid propellant were taken during combustion, and ammonium perchlorate-binder interactions were investigated. It was found that the laser source combined with a laser line filter allowed examination of the density gradient in the flame front. However, a good schlieren record could not be obtained at high power levels. The major problems were: (1) a "speckle" background effect on the high speed recording film, and (2) severe fringe pattern interference due to knife-edge problems and turbulence effects caused by the burning propellant. The monochromatic pictures demonstrated that propellants without opacifiers cannot be effectively examined for surface interactions during combustion when using high intensity laser light.

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ACKNOWLEDGEMENT

This work was sponsored by Naval Ordnance Systems Command, ORDTASK ORD-331-007/551-1/UF 33-332-303. Appreciation is also expressed to Mr. Edward Michelson for his assistance in conducting the experiments.

I. INTRODUCTION

Numerous investigations of composite solid propellant combustion which use ammonium perchlorate (AP) as the oxidizer have been conducted. These investigations have attempted to confirm particular models or have been conducted to provide additional information for more adequate modeling. Two dimensional ammonium perchlorate-binder sandwiches have been extensively utilized since AP-binder interaction of various fuel-oxidizer combinations can be efficiently examined by optical methods.

Although much information has been obtained concerning AP-binder interactions, several areas need further investigation. Two such areas are the direction of primary heat transfer in the flame front, and the AP-binder interactions during actual combustion.

Previous research in AP-binder sandwich combustion has been conducted using high-speed motion picture photography and post-fire examination of quenched samples using a scanning electron microscope [1-7,9]. In order to study the behavior of the gas phase during combustion, Kennedy [8] and Murphy [10] conducted schlieren studies of AP-binder sandwich combustion. They used a Mercury arc source for the schlieren and obtained results which were in good agreement with quenched-sample data. While the gas phase was studied extensively, the AP-binder surface interactions were not directly examined,

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and due to the presence of a bright yellow "flame light", schlieren within the visible flame was not obtained.

In this investigation, a 2 watt per line argon laser was used as the light source. To filter out the flame radiation a laser line filter was placed between the combustion bomb and the high speed camera thus allowing only primary line laser light to strike the film plane. The laser was further used to illuminate the propellant surface during actual combustion so that high speed motion pictures of the burning surface could be taken.

The purposes of this investigation were (a) to demonstrate the application of laser light to solid propellant combustion research, (b) to further refine the apparatus and techniques of Kennedy [8] and Murphy [10] in order to more adequately study gas phase combustion phenomena, and (c) to study the AP-binder surface interactions during combustion.

II. METHOD OF INVESTIGATION

The investigation consisted of two separate experimental studies: (a) the development and utilization of a laser schlieren system to study the gas phase above the deflagrating surface, and (b) the use of the laser for illumination of the burning surface so that examination of the binder-fuel interactions could be conducted using monochromatic photography.

Propellant sandwiches were constructed using ultra-high purity ammonium perchlorate as the oxidizer and polybutadiene acrylic acid (PBAA) as the binder. Binder thicknesses of 25 to 125 microns were used in the investigation. Composite propellant samples containing large ammonium perchlorate crystals (420 micron unimodal) were also studied.

During the first phase of the investigation, the laser schlieren study was conducted using a nitrogen purged combustion bomb operated at 500 and 800 psig. A high speed motion picture was used to record the schlieren data. Each film was then examined to determine the obtainable schlieren quality and, if possible, the effects of different binder thicknesses and different combustion pressures on the flame structure.

In the second phase, the burning surface was illuminated to study the interactions of the AP/AP melt with the binder/binder melt during combustion [10]. This study was conducted

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using a large AP crystal composite propellant, as well as sandwich burners. A high-speed motion picture was taken through a laser line filter for each test run.

III. EXPERIMENTAL APPARATUS AND PROCEDURES

A. PROPELLANT SPECIFICATIONS

Specifications for the ammonium perchlorate and composite propellants utilized in this investigation are given in Tables I(a) and I(b). The binder used to construct the sandwich burners consisted of 84% PBAA and 16% Epon 828 by weight. The sandwiches were cured for 96 hours at 72°C with the first three hours in a vacuum in excess of 28 in. Hg.

B. AP WAFER AND SANDWICH FABRICATION

AP wafer and binder fabrication were conducted as per References 7 and 8.

Finished sandwiches were measured for height, width, binder thickness, and optical depth (see Fig. 3) with a Gaertner Scientific Corporation measuring microscope.

C. LASER SCHLIEREN SYSTEM

The basic schlieren system, combustion bomb apparatus, and high speed camera set up are discussed in References 8 and 10. Experimental apparatus utilized during the investigation are shown in Table II.

Due to a lack of schlieren information in the visible flame area, a 2-watt per line argon laser was substituted for the mercury arc source. A negative meniscus lens was used to expand the laser beam. The expanded beam was then passed through a focusing lens which focused the laser beam at the focal point of the first schlieren lens, thus obtaining an

expanded parallel beam of light through the test section. A light source chopper [10] was also located at this point (see Fig. 1).

A neutral density wedge filter and a conventional knife-edge were used in an attempt to obtain schlieren information using the argon laser as the light source. Both objects were mounted on an adjustable platform with micrometer adjustments available in the horizontal and transverse directions. A laser line filter was located between the knife-edge and the 610-millimeter focusing lens. This lens focused the sandwich burner image on the film plane and gave a magnification of 0.8.

Sandwich burner ignition was accomplished by placing a nichrome resistance wire across the top of the burner. Ignition, camera operation, and combustion bomb pressurization were accomplished from behind a safety shield (see Fig. 2).

A Hycam camera with 16 mm film, model K2004E-115, operated at 7500 frames per second was used to record all schlieren information. Kodak Ektachrome 7241, ASA 40, high speed color film was used in all photography.

D. MONOCHROMATIC PHOTOGRAPHY

Apparatus set-up and the combustion bomb window orientation are shown in Figs. 4 and 5.

The propellant was mounted on the pedestal so that the camera looked directly at the burning surface (Fig. 6). Ignition was accomplished using a nichrome resistance wire placed

across the propellant surface. To aid in ignition, a black powder/glue/acetone mixture was then placed over the wire. This prevented the nichrome wire from igniting the propellant in a thin line and burning in a "trough".

A 2.8 to 1, f1.9 Kern-Paillard lens and a 35 millimeter extender tube were used to focus the propellant on the film plane. The laser line filter was placed immediately in front of the lens.

Camera, film and operational techniques were the same as mentioned in the preceeding section except that the camera was operated at 400 frames per second.

IV. RESULTS AND DISCUSSION

A. LASER SCHLIEREN

This section will discuss problems generated by the laser light itself, and specific problems encountered while trying to adapt the use of laser light to a schlieren system.

Due to the inherent danger of eye damage using a laser light source of high power, safety goggles are a mandatory requirement. However, when goggles are employed it is impossible to see any schlieren or to make any fine adjustments in schlieren quality. As a first attempt to solve this problem, a neutral density filter was used, and the goggles removed when checking the schlieren quality. This method worked fairly well but even at low power the brilliance of the reflected image was too intense to allow thorough examination of the schlieren quality. This problem was further compounded when the 610 mm focusing lens and camera were put into the system (see Fig. 1).

The solution to this problem was to use an orange viewing screen. The orange viewing screen made the 4880 wavelength light of the argon laser visible while wearing the safety goggles. This allowed simple determination of correct knife-edge position and examination of the schlieren quality.

A further problem encountered when using the argon laser as the schlieren light source was a "speckle" background effect that occurred on the high speed film (see Fig. 7).

While this effect remained constant throughout a data run, it made interpretation of schlieren data extremely difficult.

This effect generally results from apparent individual scattering centers and the grain size depends upon the apertures of the schlieren system [11]. Two other possible causes of the "speckle" background were interference effects due to the long coherence length of the laser light, and minute dust particles settling on the laser cavity mirrors. The latter problem, when encountered, was intensified by any subsequent imperfections in the schlieren system and therefore the laser mirrors were cleaned frequently.

The main problem that occurs when laser light is used for schlieren observations is that the light does not obey the hypotheses of geometrical optics [12]. This is due to the parallel, monochromatic and long coherence length characteristics of laser light. The undistorted images that occur at the foci of the schlieren system are extremely small, being on the order of the diffraction patterns caused by the confining apertures.

A conventional knife-edge was used to examine both burning propellant samples and a candle flame. When density variations are present in the test section, a pattern of closely spaced fringes occurred rather than a smooth transition from light to dark, which is normally characteristic of schlieren data. The turbulence that existed in ammonium perchlorate/ binder sandwich combustion caused extensive fringe patterns

and this combined with the "speckle" effect yielded little useful data. A candle flame showed a more characteristic schlieren pattern with little distortion due to fringe patterns. This is due primarily to the laminar flame associated with the burning candle (see Fig. 8).

Further, due to the long coherence length of the laser light source, the light tended to diffract around the sharp edges of the two-dimensional propellant sample. This effect, combined with the fringe patterns, made determination of the actual burning surfaces extremely difficult (see Fig. 9).

In both of the preceeding pictures and all others presented, the visible "flame light" has been eliminated. This would permit the observation of the density gradient in the visible flame if a smooth continuous schlieren could be obtained.

In an attempt to alleviate the diffraction pattern interference which occurred with the use of a conventional knife-edge, a neutral density linear wedge filter was placed in the system at the focal point of the second schlieren lens. In effect this allows the removal of the single straight edge associated with the conventional knife-edge which tends to strengthen the diffraction pattern. The result was good schlieren data with only minor fringe pattern effects due to propellant surface imperfections and diffraction pattern interference within the neutral wedge filter.

These results were obtained at extremely low power (below 0.25 watts) but at any power setting above this minimum value

the concentrated beam destroyed the vacuum deposited metallic coating material of the wedge filter. The present laser had a minimum power of 0.35 watts when properly tuned to the 4880 wavelength of light and was thus destroying the filter.

A similar phenomena occurred when a standard reflective type neutral density filter was utilized. With the beam located at the edge of the filter material, good schlieren data was obtained but the neutral density material was rapidly destroyed by the concentrated laser beam.

A possible solution to both of the above problems would be the use of a more heat resistant coating. No further investigations were conducted with the laser schlieren because of time limitations.

Oppenheim et al [12] have discussed the problems of using laser light in schlieren systems. They used a linear neutral density wedge filter in conjunction with a continuous gas laser and obtained schlieren data of a free jet flame with limited fringe patterns. This work was done at sufficiently low power to avoid damage to the filter material.

For high power study, Oppenheim et al used a prism of quartz which rotated the plane of polarization of the laser beam. The final direction of rotation was dependent on the thickness of the prism and therefore, on the position of the incident beam on the prism. A sheet of polaroid placed anywhere beyond the prism provided a variation of light transmission from complete transmission to extinction. The study was conducted using a pulsed ruby laser, and a clear detailed

schlieren record was obtained without damage to the experimental apparatus and without any appreciable fringe patterns.

Several possible alternatives are available for further study in an attempt to develop a useful and viable laser schlieren system. A quartz prism and polaroid system similar to that used by Oppenheim et al [12] should be attempted. The required prism angle is a function of the wavelength of the laser source.

Another material which may be employed as a knife-edge is a wedge or prism made of an absorbing type neutral density material. The distance of light travel through the prism, deflection angle and point of incidence would determine the quality of schlieren obtainable. The wedge must be made of heat resistant material or the intensity of the concentrated laser beam will destroy the wedge.

Both a quartz crystal and a neutral density prism have been ordered for future work at the Naval Postgraduate School.

A third recommendation for further study is the use of a piece of "photostress" material and a piece of polaroid. This method employs the use of a birefringent material similar in principle to the quartz crystal. While this method was briefly examined in this investigation, it was not studied extensively enough to determine its validity.

B. MONOCHROMATIC PHOTOGRAPHY

Using laser light for photographic observation of a burning propellant surface was hindered by several factors. In the first attempt to illuminate the propellant surface for

photographic examination, the laser beam was directed onto the propellant surface (see Fig. 4). This proved to be unsatisfactory for two reasons. First, the beam was so small that insufficient light was available to determine the actual shape and orientation of the burning surface (see Fig. 10). Second, due to the high intensity of the laser beam, the propellant was induced to burn in a hole rather than in a planar fashion. To correct for the narrow beam width in the test section, the beam was passed through a spatial filter and then a collimating lens. This yielded a beam slightly larger than the propellant sample and allowed propellant shape and orientation to be determined. Further, the wider beam eliminated the tendency of the propellant sample to burn in a hole (see Fig. 11).

Another problem that occurred was that the original propellant examined, N-3 (see Table I(b)), was translucent to the argon laser light. The light appeared to be absorbed and reradiated making it impossible to obtain sharp focus on the propellant surface. Since it was desired to study non-metallized propellant, this proved to be a major problem.

In an attempt to determine if the actual technique was feasible, a metallized propellant, N-8 (see Table I(b)), was examined. This propellant worked satisfactorily and a sharp picture of the propellant surface was obtained (see Fig. 12).

The final problem area was smoke obscuration of the burning surface during combustion. Earlier work of Schroeder [13] and Willoughby [14] discuss the problem of high speed motion

picture photography in an acceleration environment, and utilizing an aluminized propellant. The technique used was to place the propellant sample at a high angle with respect to the camera film plane. They obtained excellent surface definition utilizing this technique.

In this investigation a similar technique was employed. However, a nonmetallized propellant was burned in a nonaccelerated environment and smoke obscuration was a greater problem. While several data runs gave a clear view of the burning surface, the surface was out of focus due to the critical nature of camera focusing using extender tubes.

Further work in this area is recommended since the technique appears capable of yielding useful data on propellant burning characteristics during actual combustion without interference from the visible flame light.

V. CONCLUSIONS

1. Use of a proper colored screen allows safe examination of laser schlieren sensitivity and focus.

2. The "speckle" effect visible on high-speed motion picture film is a major deterrent to obtaining useful schlieren data.

3. A conventional knife-edge cannot be used to examine highly turbulent gas phase phenomena because of the resulting severe fringe patterns.

4. At a power setting above 0.25 watts, currently available reflective type linear neutral density wedge filters cannot be used as a knife-edge.

5. By utilizing a laser line filter, the "visible flame" can be removed from high-speed motion picture studies, permitting study of the density gradient in the flame front.

6. Surface phenomena occurring in the combustion of non-metallized composite propellants which do not contain opacifiers will be difficult to study photographically using high intensity laser light.

7. While the "flame light" can be removed, smoke obscuration of the burning surface hinders observation of the surface interactions during combustion.

In conclusion, it appears that the laser can become a useful instrument for the study of solid propellant combustion. Further work is necessary to determine effective material to replace the conventional knife-edge in the schlieren system.

[illegible]

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TABLE I(a) AP SPECIFICATIONS

Designation	Crystal Size	Principal Impurities (wt%)
UHP (ultra high purity)	38.1% > 297μ	Sulfated Ash 0.01%
	81.9% > 211μ	
	99.6% > 104μ	

TABLE I(b) PROPELLANT SPECIFICATIONS

Designation	Binder (Ingredients & wt%)		AP (size & wt%)	Additives (size & wt%)	Manufacturer
N-3	PBAN	21%	420-500μ 79%	none	NWC, China Lake
N-8	PBAN	18%	420-500μ 67%	Aluminum 44μ 15%	NWC, China Lake

TABLE II EXPERIMENTAL APPARATUS

Schlieren and Monochromatic Photography light source	Control Laser Model 902A Argon CW Ion Laser
Film	Kodak Ektachrome 7241 ASA 40
Laser Line Filter	Corion Instrument Corp. 100-4880-1 Filter
Camera	400 ft, 16 mm Hycam camera frame rate 400-7500 shutter 1/2.5
Knife-edge	1. Conventional knife-edge 2. Optical Industries Rectangular Neutral Density Linear Wedge Filter Range: 0.0-1.0
Schlieren focusing lens	610 mm, f6
Monochromatic Photography focusing lens	Kern-Paillard YVAR 2.8 to 1 f=75 mm AR
Extension Tubes	Paillard-Bolex 5 mm 10 mm 20 mm

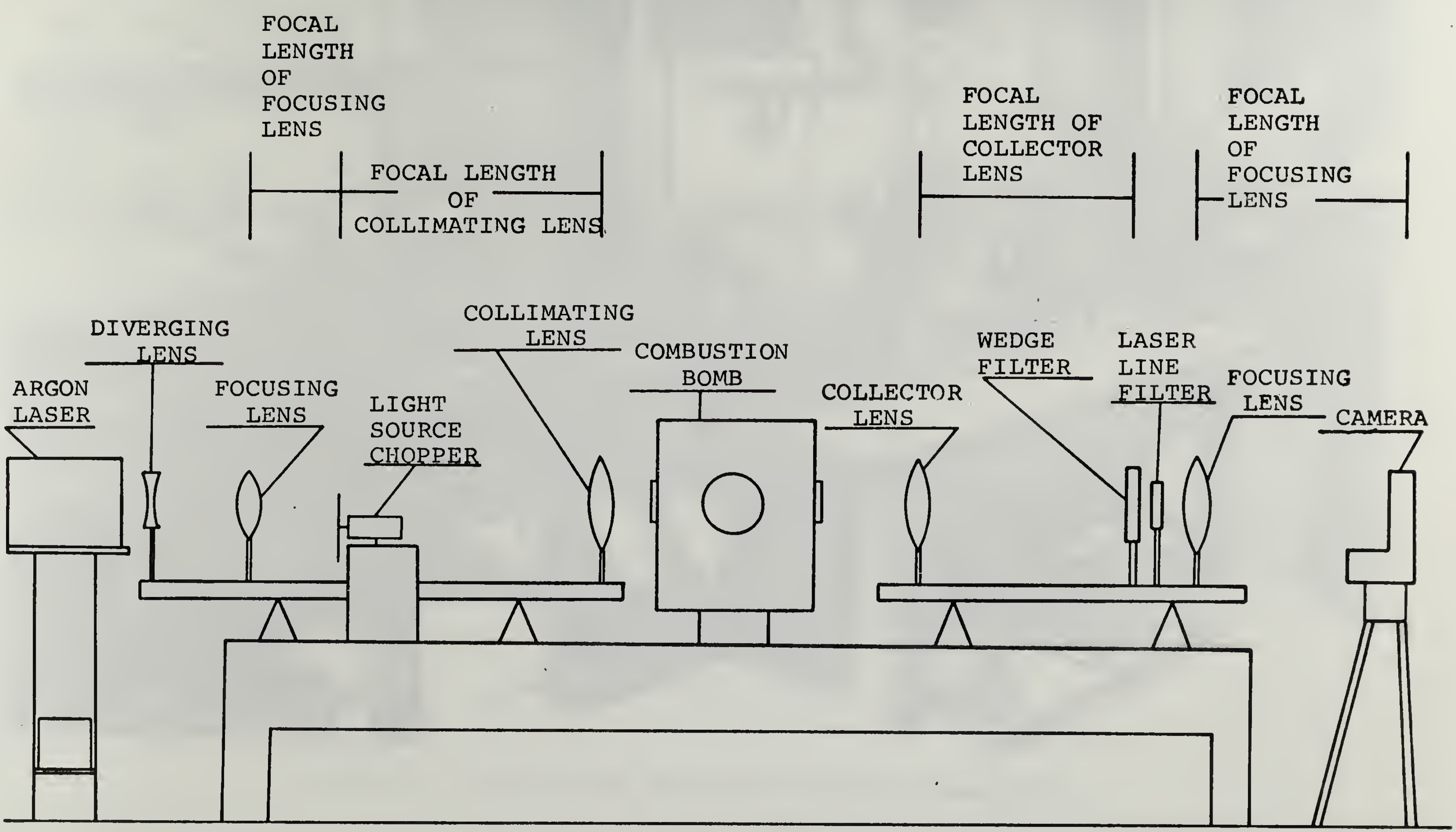


Figure 1. Schematic of Laser Schlieren

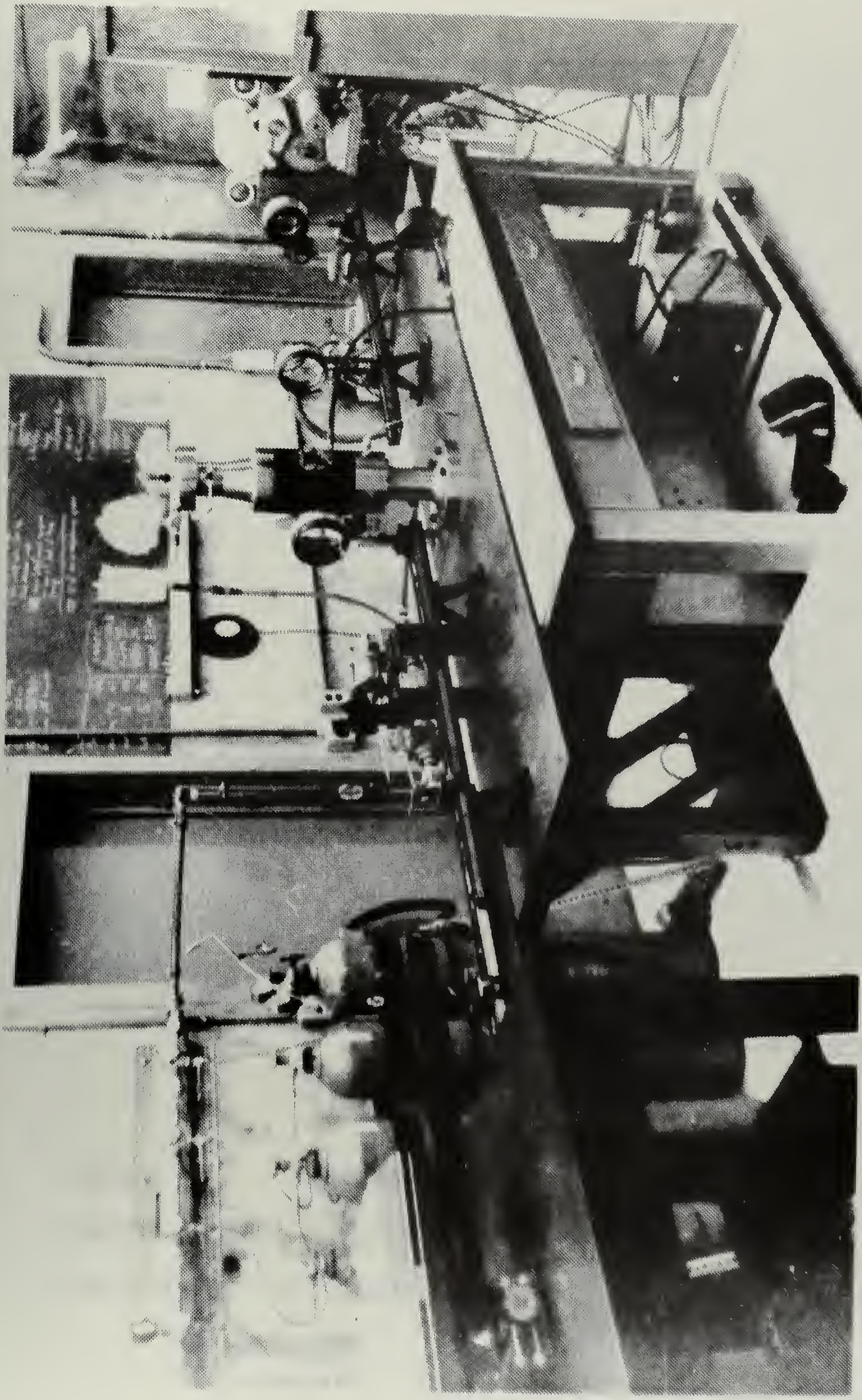
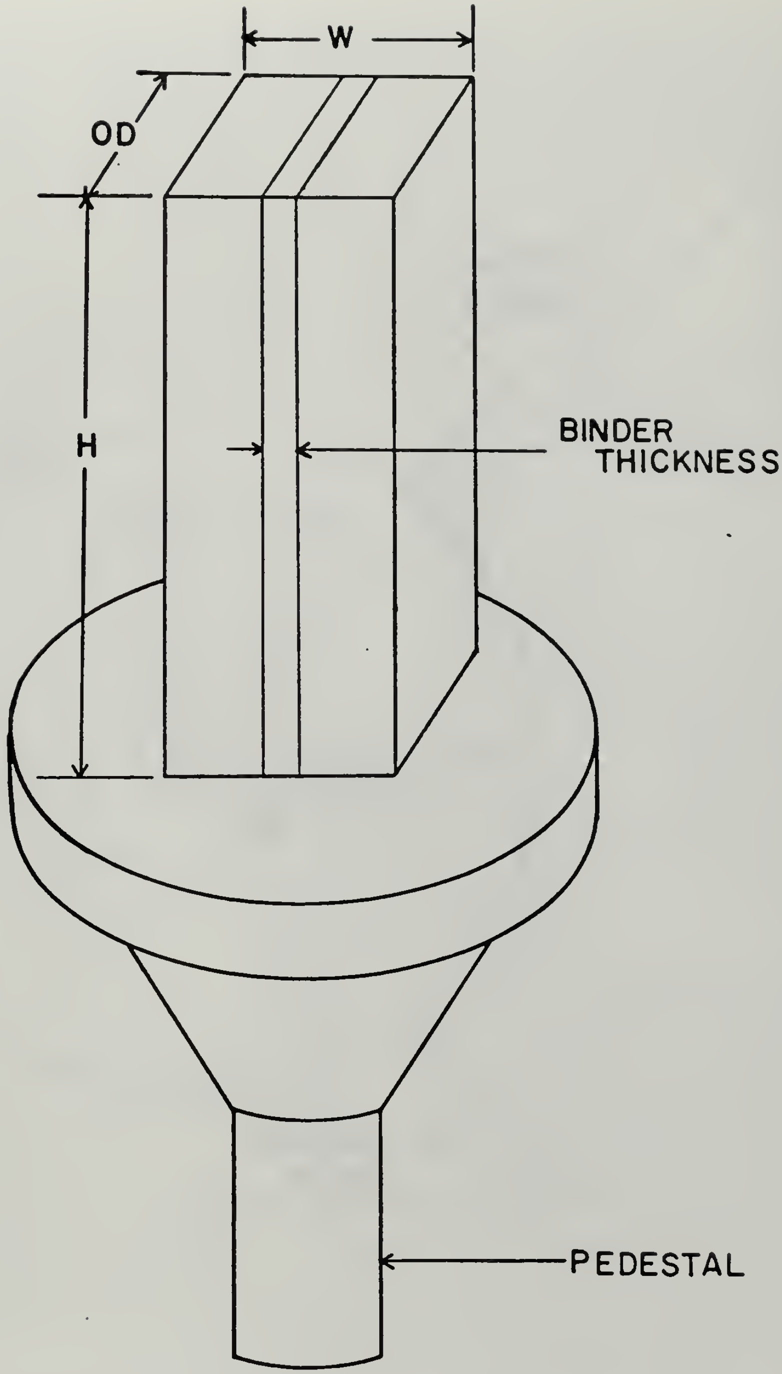


Figure 2. Photograph of Laser Schlieren Apparatus



HEIGHT	0.356 to 0.393 in.
WIDTH	0.104 to 0.114 in.
OPTICAL DEPTH	0.041 to 0.056 in.

Figure 3. Schematic of Sandwich Burner

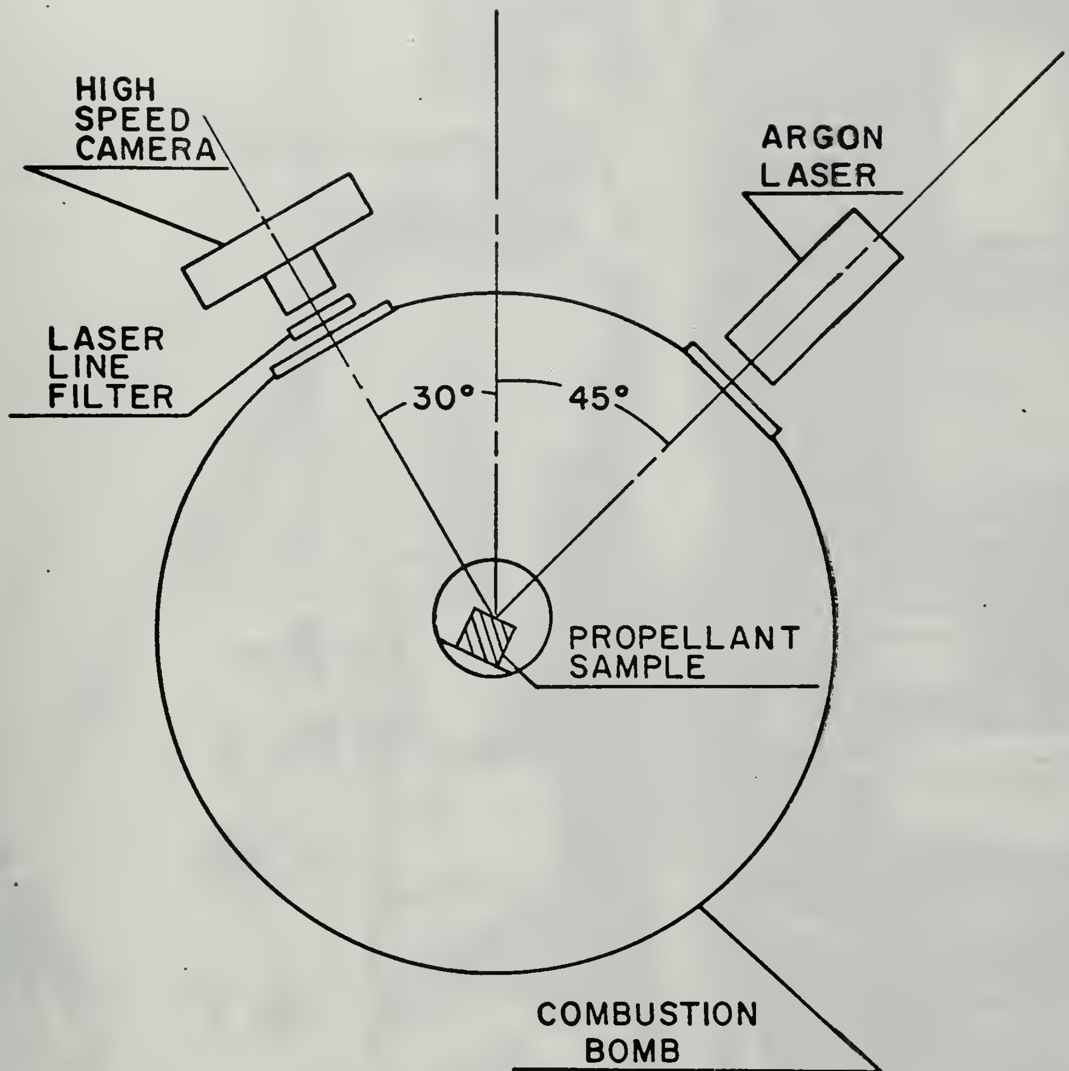


Figure 4. Schematic of Apparatus for Monochromatic Photography

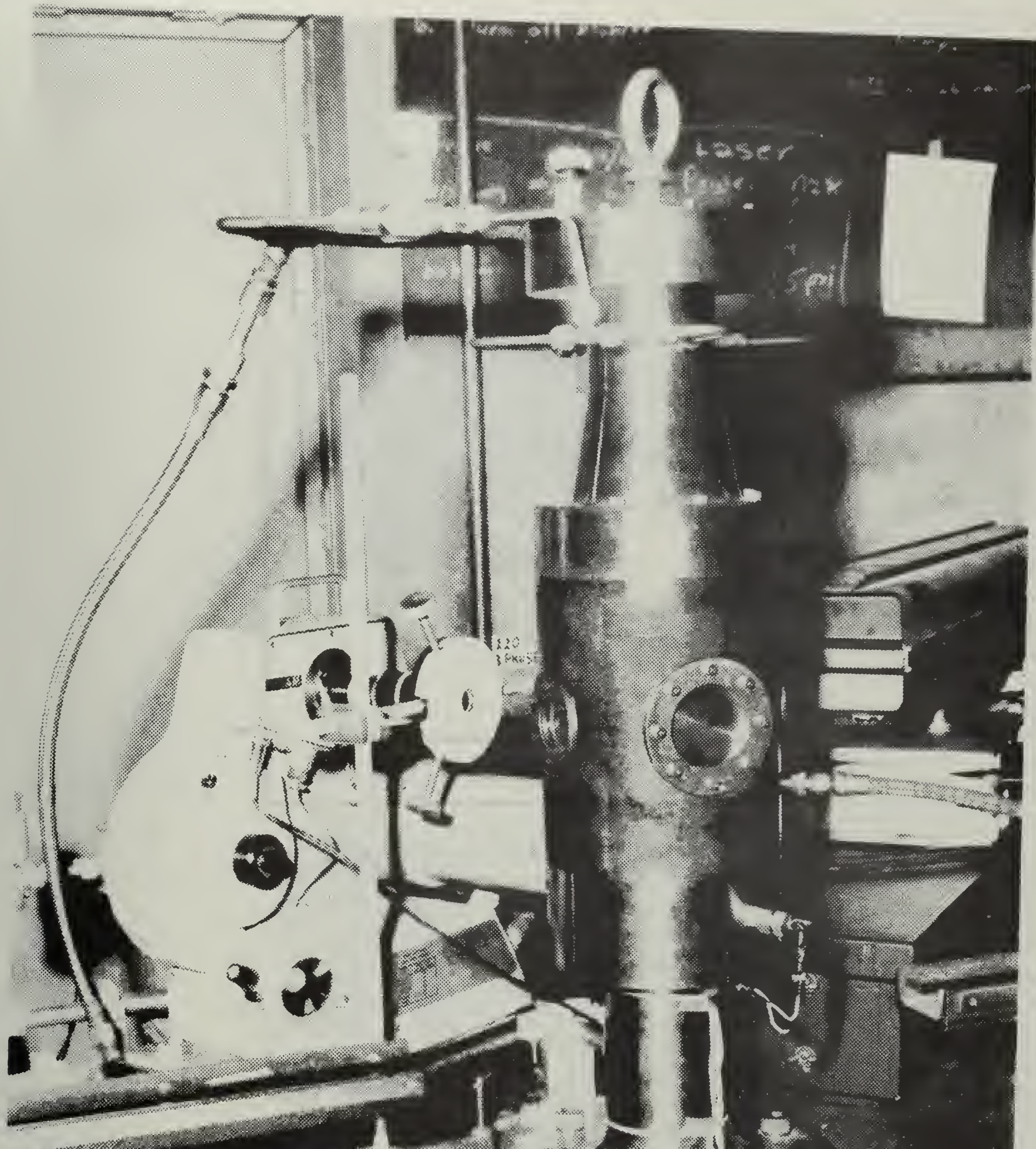


Figure 5. Photograph of
Monochromatic Photography Apparatus

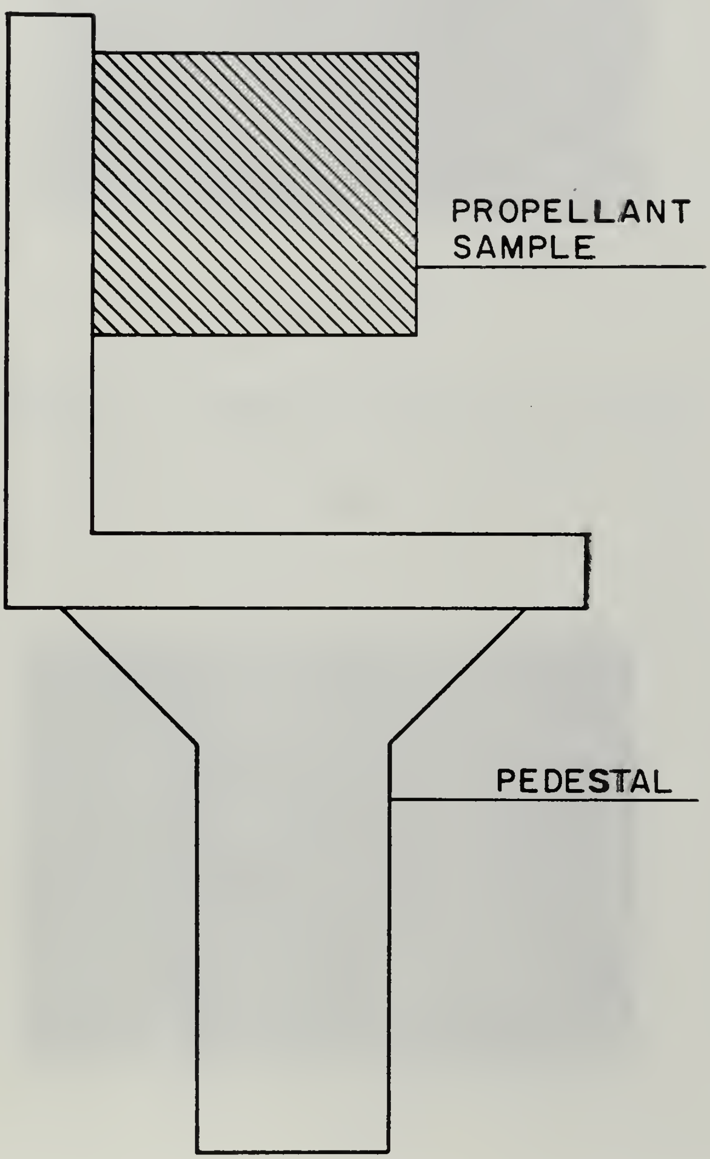


Figure 6. Propellant Mounting for Monochromatic Photography

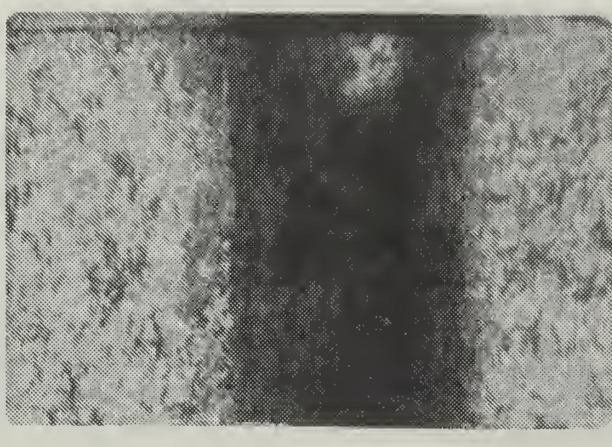
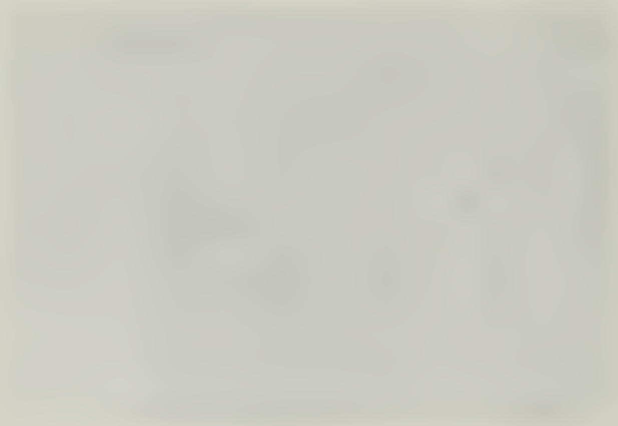


Figure 7. "Speckle" Background Effect

Figure 8. Laser Schlieren of Candle Flame Burning at Atmospheric Pressure



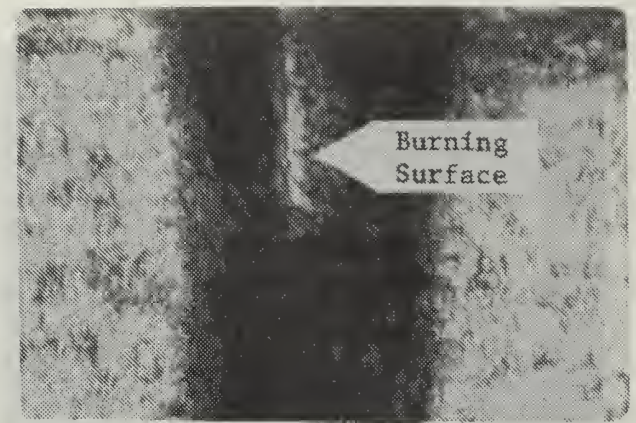


Figure 9. Laser Schlieren of PBAA/AP Sandwich Burning at 100 psig

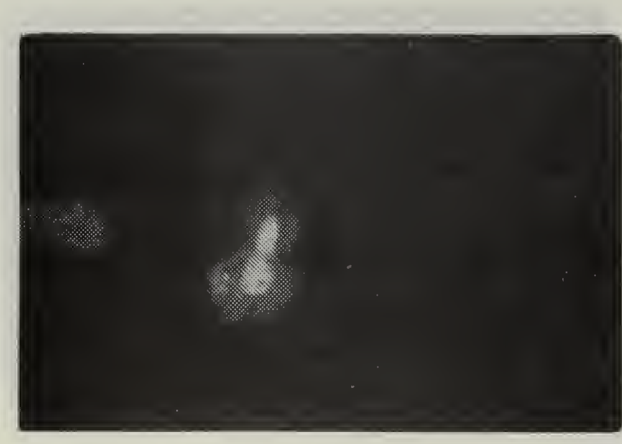


Figure 10. Concentrated Laser Beam Illumination of N-3 Burning at 100 psig

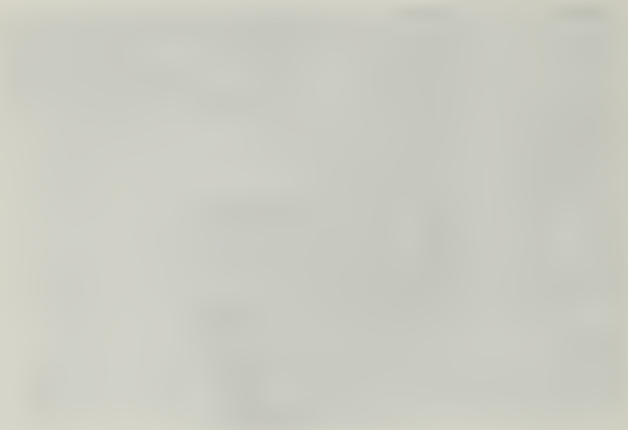


Figure 11. Expanded Laser Beam Illumination of N-3 Burning at 100 psig

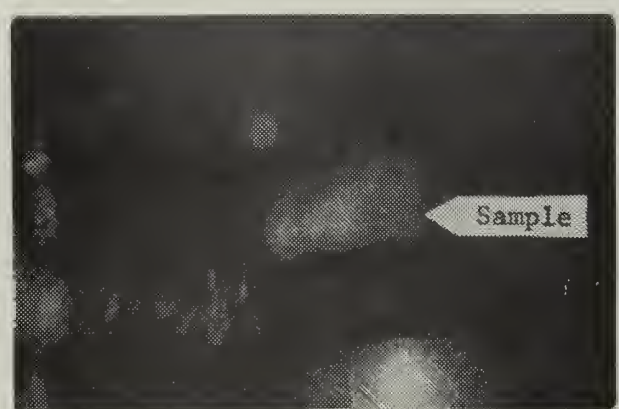
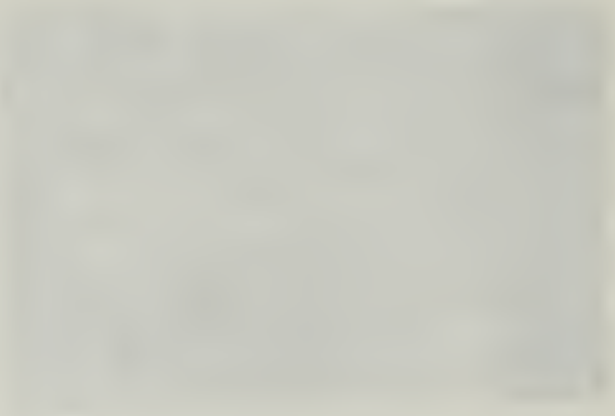
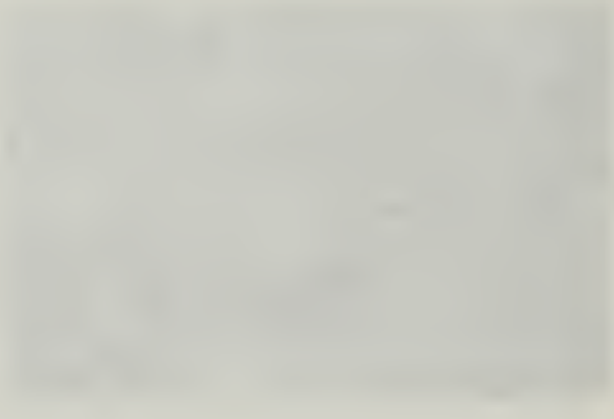


Figure 12. Expanded Laser Beam Illumination of N-8 Burning at 100 psig





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Ammonium perchlorate (AP)-binder sandwiches and a composite propellant were burned in a combustion bomb at various pressures. A schlieren system equipped with an argon laser was used to study the flame structure. High speed monochromatic motion pictures of solid propellant were taken during combustion, and ammonium perchlorate-binder interactions were investigated. It was found that the laser source combined with a laser line

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filter allowed examination of the density gradient in the flame front. However, a good schlieren record could not be obtained at high power levels. The major problems were: (1) a "speckle" background effect on the high speed recording film, and (2) severe fringe pattern interference due to knife-edge problems and turbulence effects caused by the burning propellant. The monochromatic pictures demonstrated that propellants without opacifiers cannot be effectively examined for surface interactions during combustion when using high intensity laser light.

Klahr

Application of laser schlieren and monochromatic photography to solid propellant combustion research.

Thesis
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Klahr

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